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# $B_s$ Mixing at CDF

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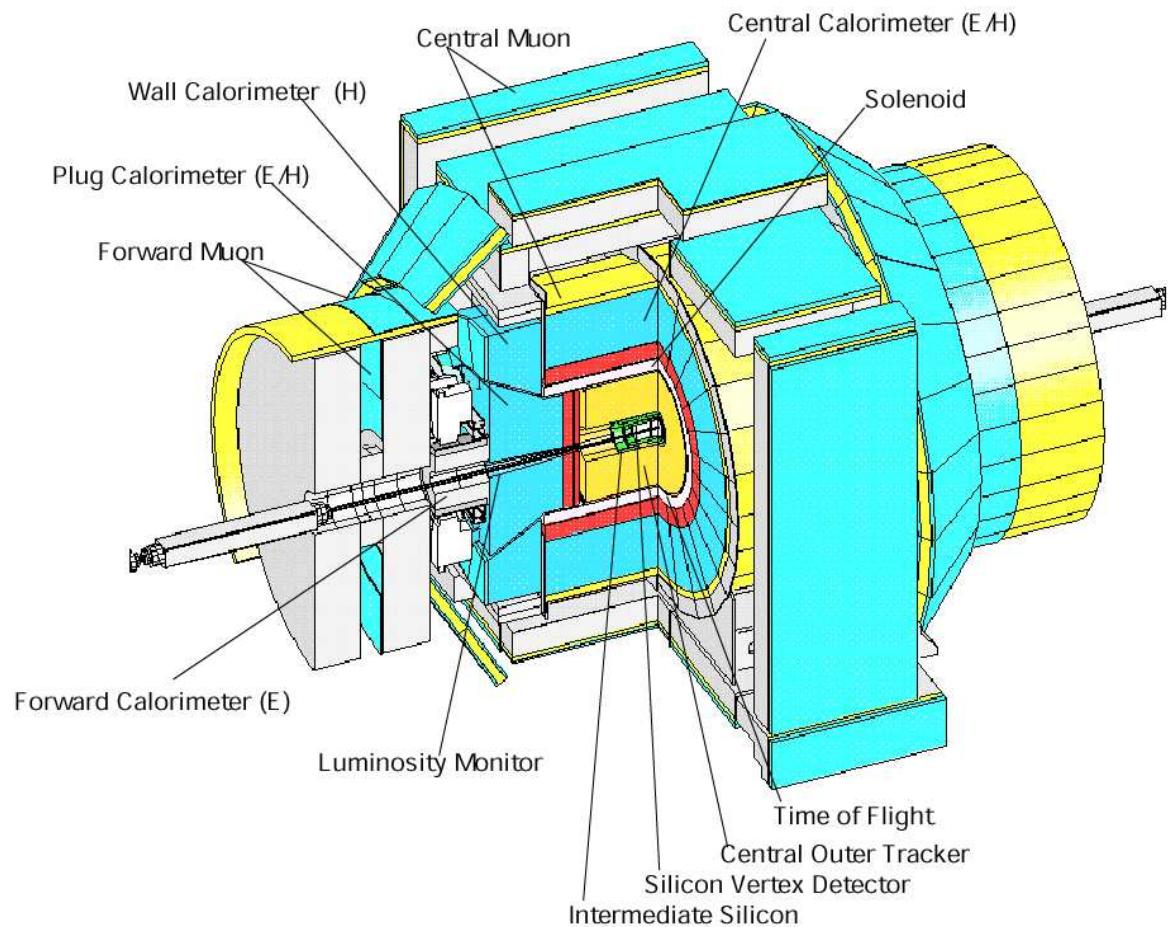
Massachusetts Institute of Technology  
for the CDF Collaboration

FPCP 2004

Daegu - Korea

New detector components:

- Tracking System
  - 3D Silicon Vertex Detector ( $|\eta| \leq 2$ )
  - Drift Chamber
  
- Time of Flight (particle ID)
- Plug & Forward Calorimeters



- DAQ & Trigger systems
   
 (Online Silicon Vertex Tracker:  
 trigger on displaced vertices)

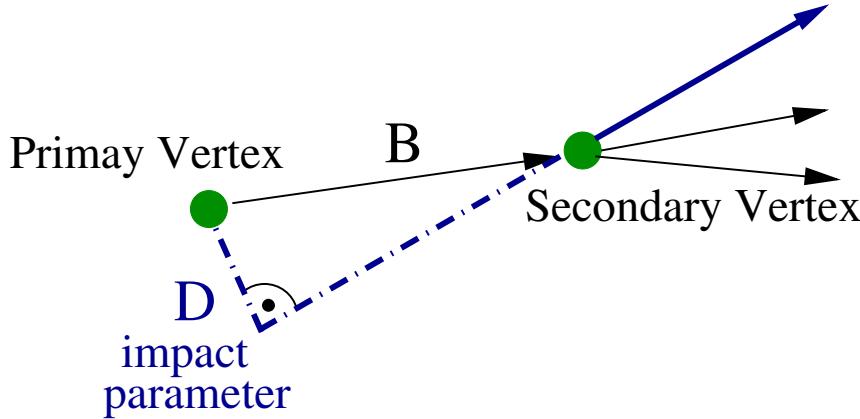
## Conventional

### Di-Muon ( $J/\Psi$ )

- $P_t(\mu) \geq 1.5 \text{ GeV}$

### $J/\Psi$ down to low $P_t$

- CP violation
- Masses, lifetimes
- Quarkonia, rare decays



New in CDF - For the first time in hadronic environment

### Displaced track + lepton $e, \mu$

- $D(\text{track}) \geq 100 \mu\text{m}$
- $P_t(\text{lepton}) \geq 4 \text{ GeV}$

### Semileptonic modes

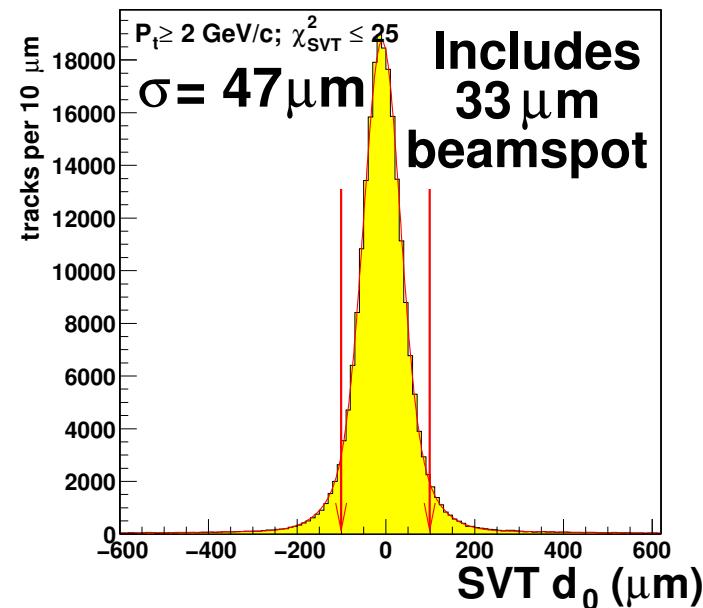
- High statistics lifetime
- Sample for tagging studies, mixing

### Two track

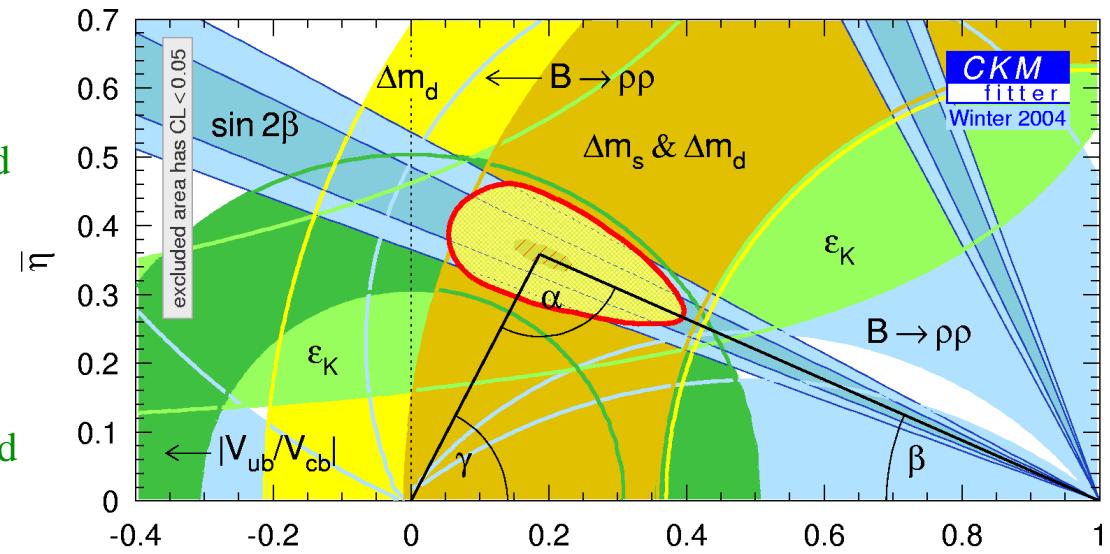
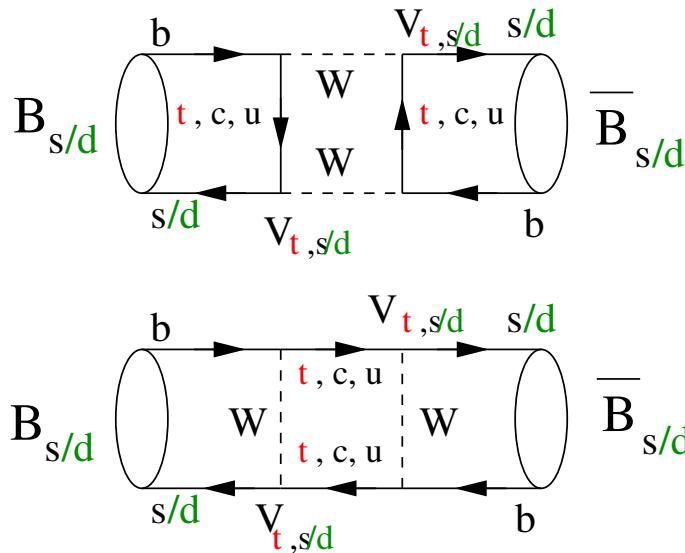
- $D(\text{track}) \geq 120 \mu\text{m}$
- $P_t(\text{track}) \geq 2 \text{ GeV}$

### Fully hadronic modes

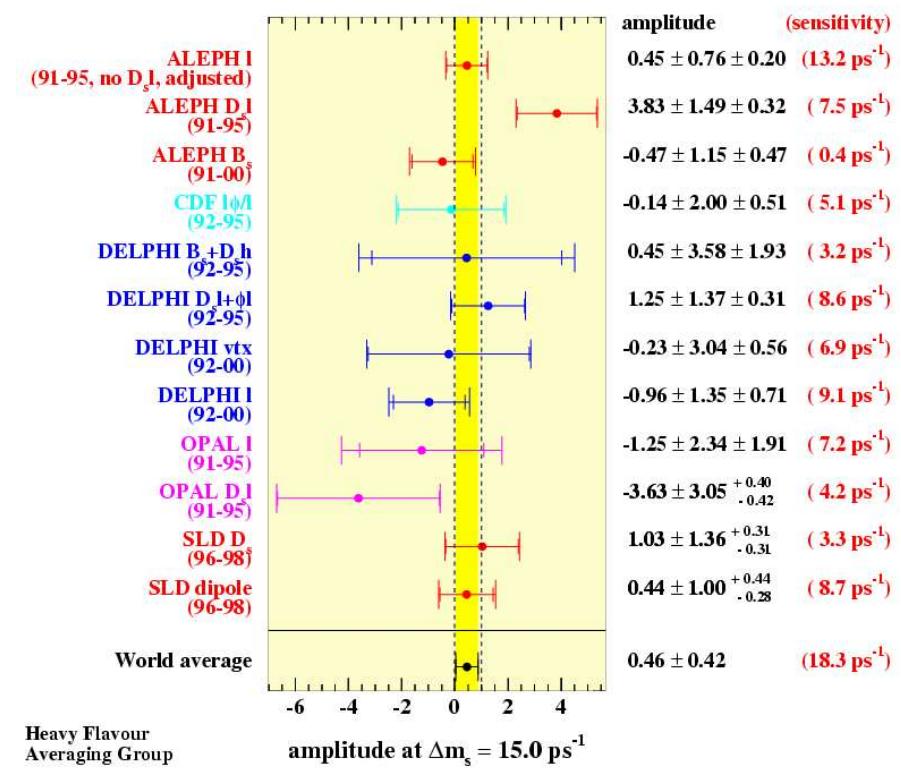
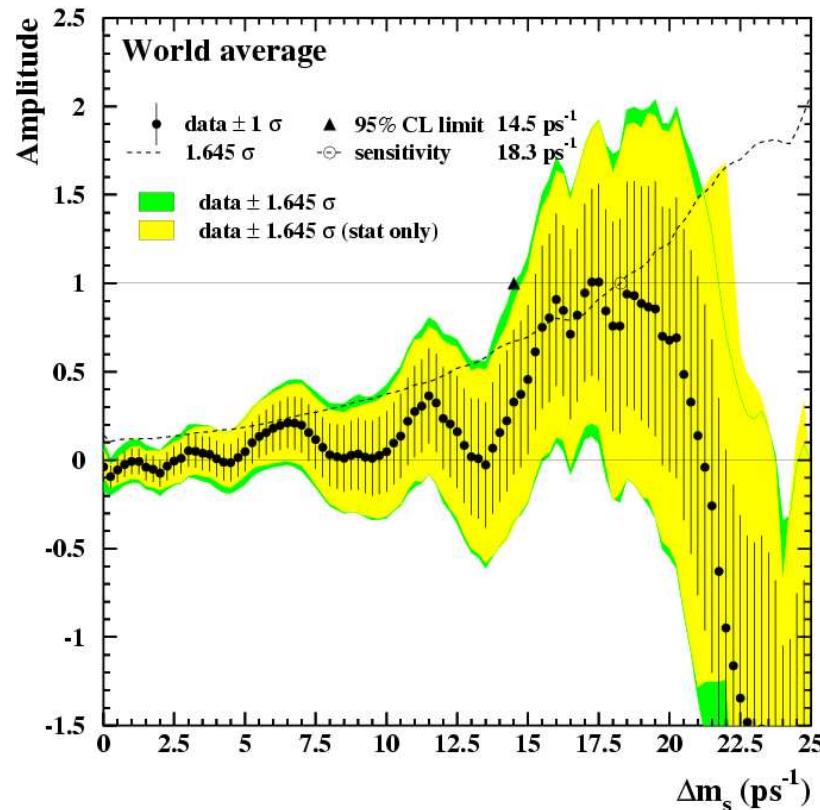
- $B_s$  mixing
- CP asymmetry in 2-body charmless decays



- $B_{s(d)}$  mixing is sensitive to  $V_{ts}$  ( $V_{td}$ )
- Constraint side of CKM triangle opposite of the angle  $\gamma$
- Most of the theoretical uncertainties cancel in the ratio  $V_{ts}/V_{td}$
- $\Delta m_s$  required for time dependent  $B_s$  CP violation
- New Physics may affect  $\Delta m_s/\Delta m_d$



# Current Experimental Results on $\Delta m_s$



Winter 2004 summary:

- Limit:  $\Delta m_s \geq 14.5 \text{ ps}^{-1}$
- Sensitive up to  $\Delta m_s = 18.3 \text{ ps}^{-1}$



# Ingredients for Mixing

In order to measure:

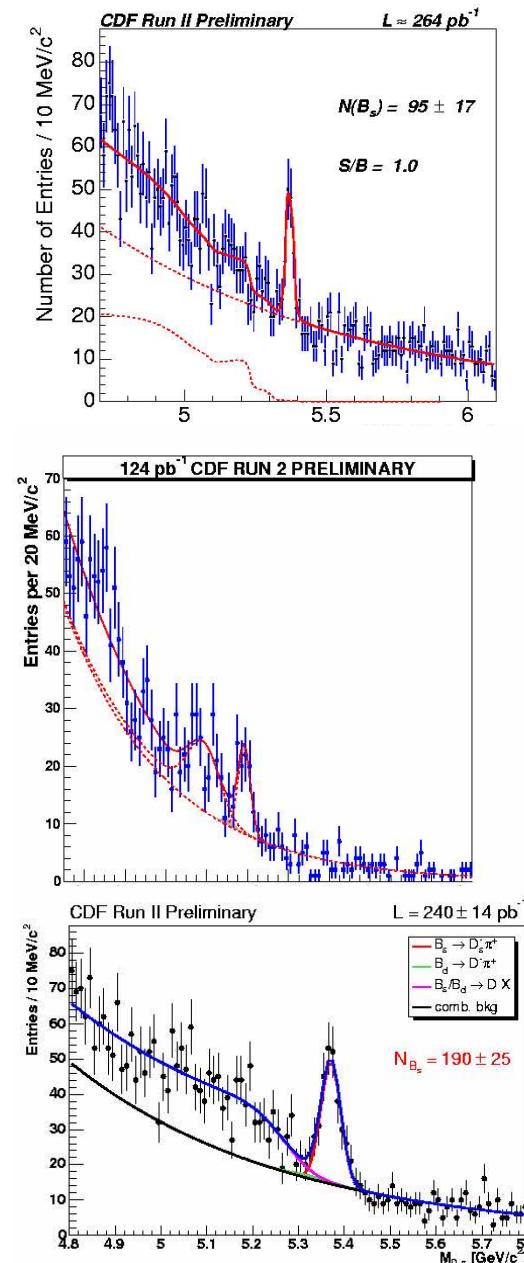
$$\begin{aligned} A_{mix}(t) &= \frac{N_{mix}(t) - N_{unmix}(t)}{N_{mix}(t) + N_{unmix}(t)} \\ &= -D * \cos(\Delta m_s t) \end{aligned}$$

we need:

- Considered  $B_s$  signals sofar
  - hadronic modes:  $B_s \rightarrow D_s \pi (D_s \rightarrow \phi \pi)$   
 $B_s \rightarrow D_s 3\pi (D_s \rightarrow \phi \pi)$   
 $B_s \rightarrow D_s \pi (D_s \rightarrow K^* K)$   
 $B_s \rightarrow D_s \pi (D_s \rightarrow 3\pi)$
  - semileptonic mode:  $B_s \rightarrow l\nu D_s X (D_s \rightarrow \phi \pi)$
- Flavour tagging ( $\epsilon D^2$ )  
Efficiency:  $\epsilon = \frac{N_w + N_r}{N}$   
Dilution:  $D = 1 - 2 \frac{N_w}{N_w + N_r}$

- Lifetime Measurement  
(good timing resolution)  
→ good  $L_{xy}$  resolution  
 $c\tau = \frac{L_{xy}}{\gamma\beta}; \gamma\beta = \frac{p_T(B)}{M(B)}$ ;  
 $\sigma_{c\tau} = \left( \frac{\sigma_{L_{xy}}}{\gamma\beta} \right) \oplus \left( \frac{\sigma_{\gamma\beta}}{\gamma\beta} \right) * c\tau$   
kinematic term dominant for semileptonics
- Fitting framework

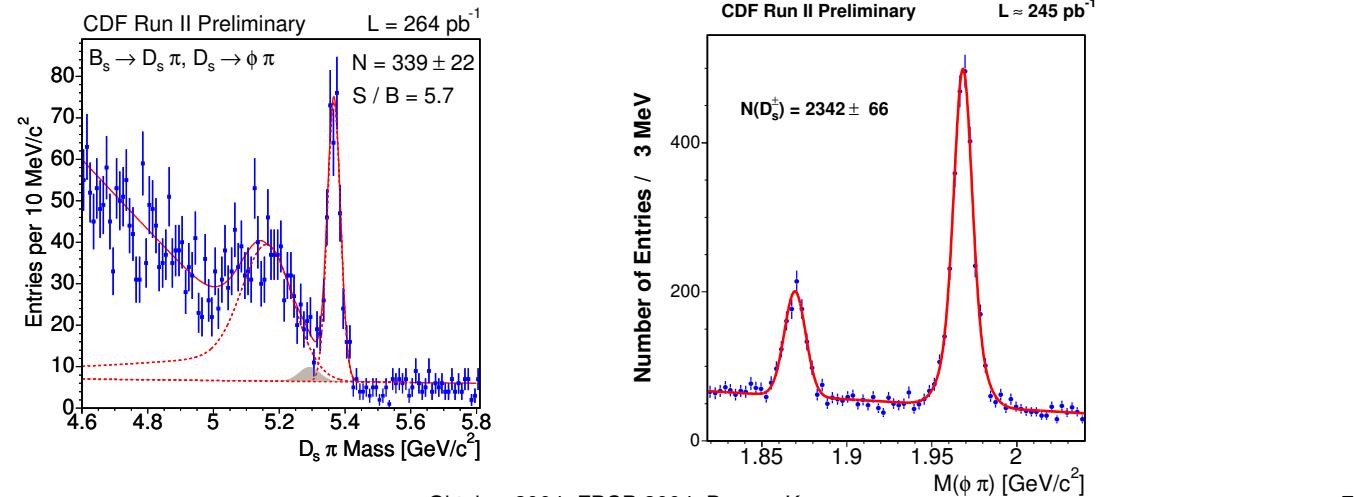
# Reconstructed $B_s$ Candidates



Number of events we have already in hand:

Channel (add. modes are considered)	# events	$L (\text{pb}^{-1})$	Yield/ $250 \text{ pb}^{-1}$	S/B
$B_s \rightarrow D_s \pi (D_s \rightarrow \phi \pi)$	$339 \pm 22$	264	320	5.7
$B_s \rightarrow D_s 3\pi (D_s \rightarrow \phi \pi)$	$95 \pm 17$	264	90	1.0
$B_s \rightarrow D_s \pi (D_s \rightarrow K^* K)$ *	$190 \pm 25$	240	200	1.3
$B_s \rightarrow D_s \pi (D_s \rightarrow 3\pi)$	$57 \pm 11$	124	115	1.75
$B_s \rightarrow l\nu D_s X (D_s \rightarrow \phi \pi)$	$2343 \pm 66$	245	2400	3.5

\*potential gain with PID for rejection  $B_d \rightarrow D^- \pi$



## Opposite Side Tagging:

- **Jet-Charge-Tagging:**  
sign of the weighted average charge of opposite B-Jet

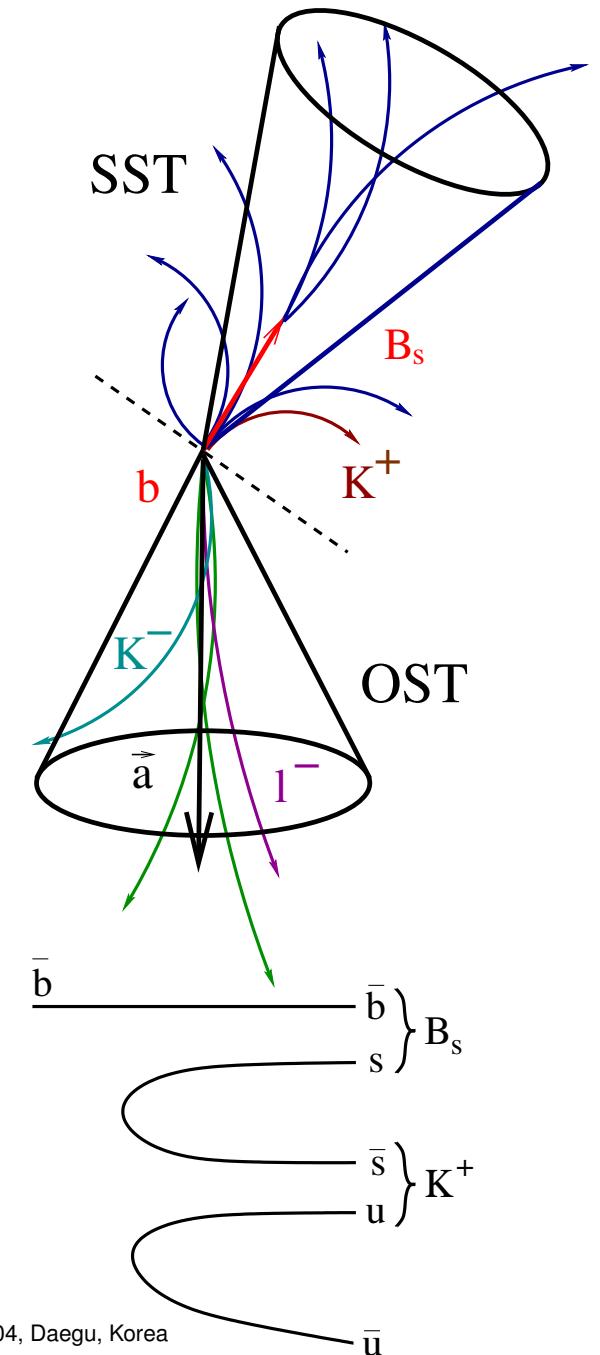
$$Q_{jet} = \frac{\sum_i q^i P_T^i (2 - T_P^i)}{\sum_i P_T^i (2 - T_P^i)}$$

$P_T$  transverse momentum;  $T_P$ : probability to be primary track

- **Soft-Lepton-Tagging:**  
identify soft lepton ( $e, \mu$ ) from semileptonic decay of opposite B:  $b \rightarrow l^- X$  (BR  $\approx 20\%$ ),  
Dilution due to  $\bar{b} \rightarrow \bar{c} \rightarrow l^- X$  and oscillation
- **Kaon-Tagging:**  
due to  $b \rightarrow c \rightarrow s$  it is more likely that a  $\bar{B}$  meson contains a  $K^-$  than a  $K^+$  in the final state

## Same Side Tagging:

- $B_s$  is likely to be accompanied close by a  $K^+$





# Opposite Side Tagging

OST performance is validated on high statistics lepton+displaced track sample

## Electron Tagging:

$$\epsilon D^2 = (0.366 \pm 0.031 \text{ (stat)}^{+0.065}_{-0.056} \text{ (syst)})\%$$

- Likelihood based on 9 discriminating variable from calorimeters, shower max detectors and dE/dx in drift chamber

$$S = \prod_{i=1}^9 S_i, B = \prod_{i=1}^9 B_i, L = \frac{S}{S+B}$$

( $S_i/B_i$ : signal/background distribution for variable i)

split sample in bins of  $L$ ,  $p_T$  and signed impact parameter

## Muon Tagging:

$$\epsilon D^2 = (0.698 \pm 0.042)\%$$

- Likelihood based on 5 variable from calorimeters and muon chambers
- split sample in bins of  $L$ , transverse momentum and muon system

## Jet Charge Tagging:

$$\epsilon D^2 = (0.715 \pm 0.027)\%$$

- split sample in subset of different jet qualities

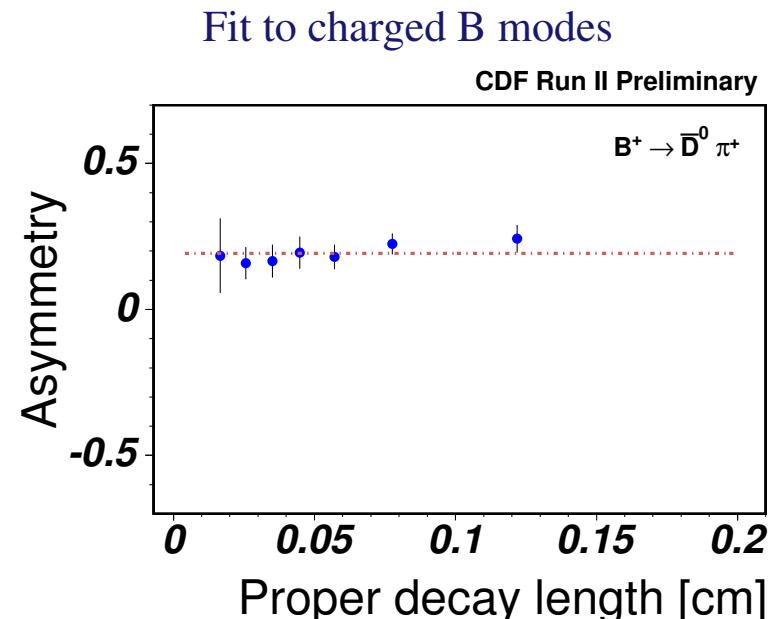
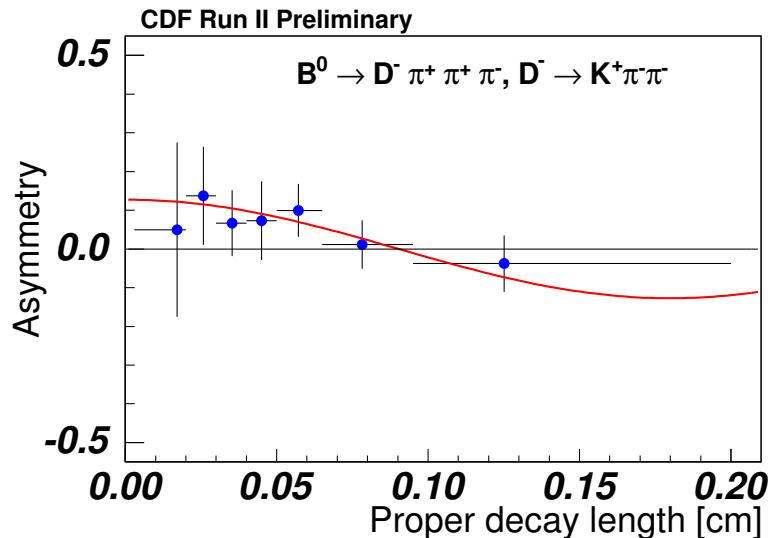
## Opposite Side Kaon Tagging

not yet available

# $B_d$ Mixing with SST

Time dependent asymmetry fit:  $A(t) = \frac{G(ct; ct', \sigma^{ct}) \otimes (e^{-t'/\tau_0} D_0 \cos(\Delta m_d ct'))}{G(ct; ct', \sigma^{ct}) \otimes e^{-t'/\tau_0}}$

Combined fit of fully reconstructed  $B_d$  modes



Decay	$\epsilon$ (%)	$D_0$ (%)	$\Delta m_d$ ( $ps^{-1}$ )
$B^0 \rightarrow J/\psi K^{*0}$	$62.0 \pm 1.5$	$16.7 \pm 5.6$	$0.487 \pm 0.125$
$B^0 \rightarrow D^- \pi^+$	$61.0 \pm 0.8$	$11.5 \pm 3.5$	$0.645 \pm 0.120$
$B^0 \rightarrow D^{*-} \pi^+$	$64.8 \pm 1.3$	$17.9 \pm 5.6$	$0.481 \pm 0.098$
$B^0 \rightarrow D^{*-} \pi^+ \pi^+ \pi^-$	$66.0 \pm 1.7$	$7.7 \pm 6.7$	$0.263 \pm 0.325$
$B^0 \rightarrow D^- \pi^+ \pi^+ \pi^-$	$68.7 \pm 1.1$	$9.7 \pm 4.8$	$0.430 \pm 0.148$

Decay	$\epsilon$ (%)	$D_+$ (%)	$\epsilon D_+^2$ (%)
$B^+ \rightarrow J/\psi K^+$	$60.3 \pm 0.8$	$19.9 \pm 2.2$	$2.39 \pm 0.52$
$B^+ \rightarrow \bar{D}^0 \pi^+$	$61.5 \pm 0.7$	$19.2 \pm 1.9$	$2.28 \pm 0.45$
Weighted average	$61.0 \pm 0.5$	$19.5 \pm 1.4$	$2.33 \pm 0.34$

$$\Delta m_d = (0.526 \pm 0.056 \text{ (stat)} \pm 0.005 \text{ (syst)}) ps^{-1}$$

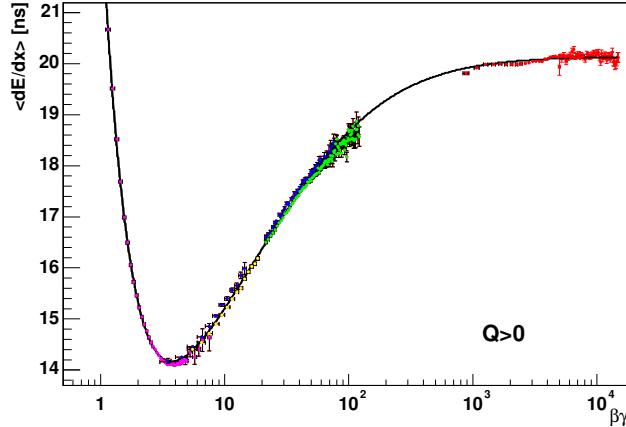
$$\text{SST: } \epsilon D^2(B^0) = (1.00 \pm 0.35 \text{ (stat)} \pm 0.07 \text{ (syst)}) \%$$

# Same Side Tagging

SST performance depends on the flavour of the signal side!

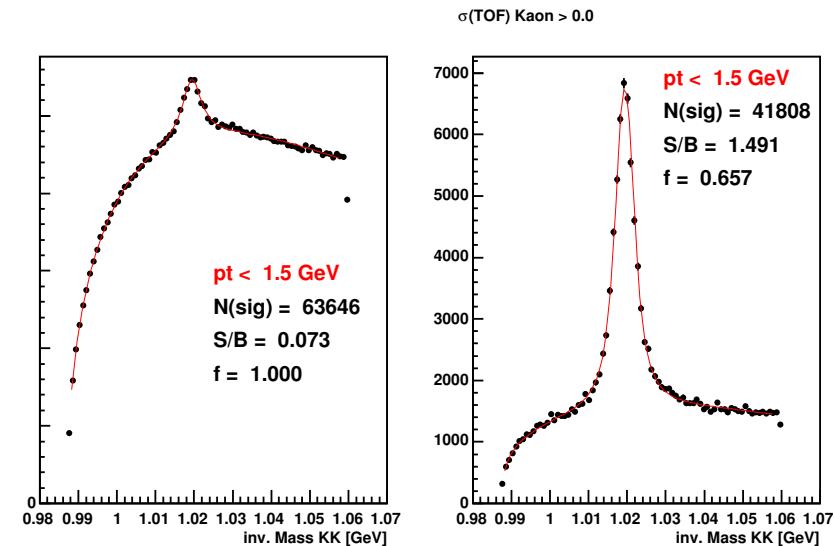
- $B^+, B^0$  different SST performance due to different fragmentation, charge, ...
- SST for  $B_s$  additional different due to  $\pi \Leftrightarrow K, B^{**}$
- Performance of SST for  $B_s$  can not be measured on data before mixing is seen
- In order to use SST for limits on  $\Delta m_s$  we need to understand MC very well ( $b\bar{b}$  production, fragmentation,  $B^{**}$  content, particle ID, ...)

But it will be a powerfull tagger and can be improved with PID



$dE/dx$  in drift chamber  $e, \mu, K, \pi, p$

S. Menzemer



Oktober 2004, FPCP 2004, Daegu, Korea



# $B_d$ Mixing with Combined Taggers

- Use high statistics channel  $B \rightarrow lD^{(*)}$  from lepton+SVT trigger sample to study taggers and validate fitter
- apply OST subsequently (1. Muon Tagger, 2. Jet-Q1, 3. Jet-Q2 \*) to avoid correlations
- assume OST and SST to be uncorrelated
- split sample in 10 subsample according to tagger desicion (OST or SST, OST and SST, both dis/agree ...)
- perform binned likelihood fit (will move on to unbinned fit soon)
- fit involves additional parameters to take cross talk ( $B^0 \Leftrightarrow B^+$ ) into account

$$\Delta m_d = (0.536 \pm 0.037(\text{stat}) \pm 0.009(\text{s.c.}^{**}) \pm 0.015(\text{syst})) \text{ps}^{-1}$$
$$\epsilon D^2(B^0)_{\text{total}} = (1.820 \pm 0.114)\%$$

\* taggers used for this study are older versions as the ones presented before

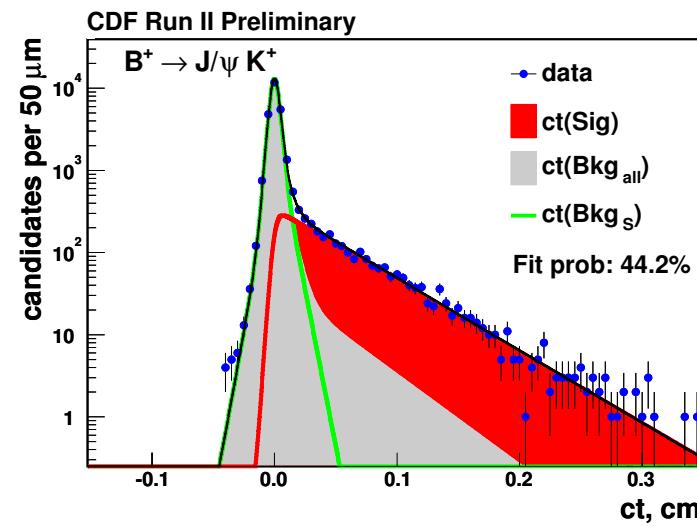
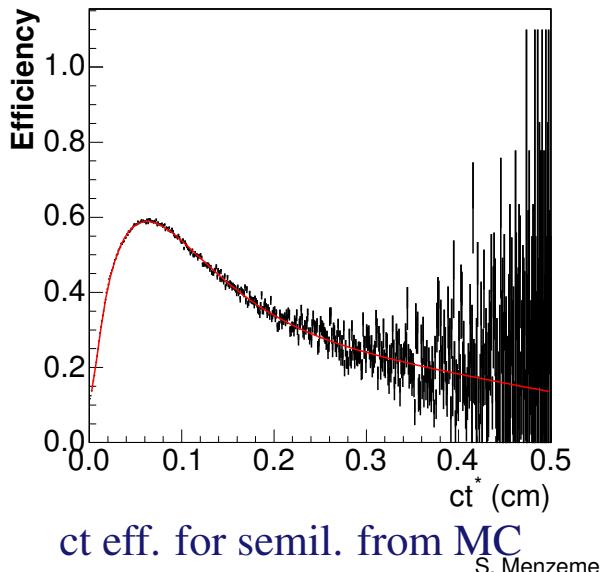
\*\* sample composition

# Lifetime Measurement

- Hadronic and semileptonic samples have lifetime bias due to SVT trigger  
→ include  $ct$  efficiency into fit
- Need to cross-check lifetime measurements on unbiased sample  
(e.g.  $B^+ \rightarrow J/\Psi K^+$ )
- Have to correct for incomplete reconstruction for semileptonics

$$ct = \frac{L_T(B_s)M(B_s)}{p_T(B_s)} \quad K = \frac{p_T(lD_s)}{p_T(B_s)} \quad \frac{\sigma(K)}{K} \approx 15\%$$

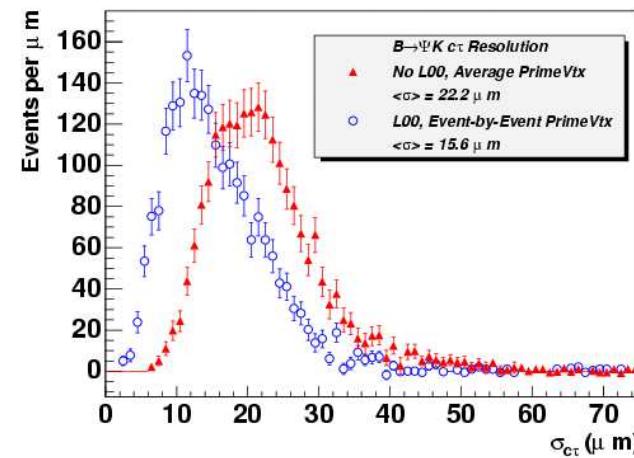
$$= \frac{L_T(B_s)M(B_s)}{p_T(lD_s)} K \quad \sigma_t = \sigma_{t_0} \oplus t * \frac{\sigma(K)}{K} \quad (\text{from MC})$$



# $B_s$ Mixing Projections (I)

Taggers:	SMT	SET	JQT	SST	Total	Projection
$\epsilon D^2$ (%)	0.7	0.35	0.5	1	1.6 (2.6)	1.6 (2.6)

$L_{xy}$  Resolution:  
with & w/o event vertex  
and Layer 00:  $22.2 \mu\text{m} \rightarrow 15.6 \mu\text{m}$



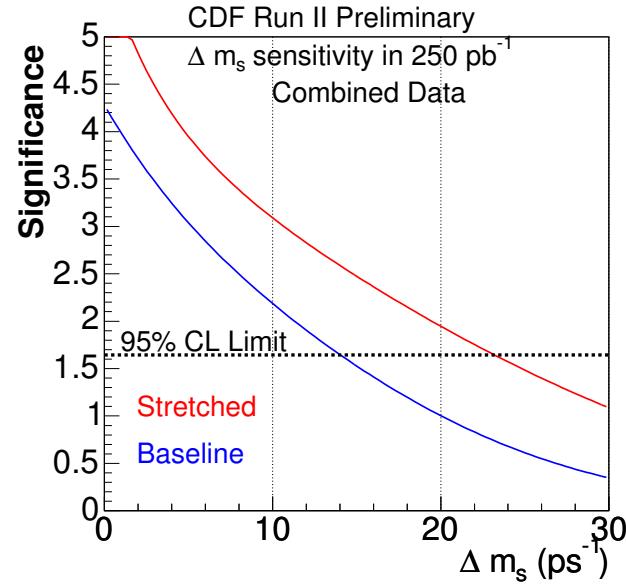
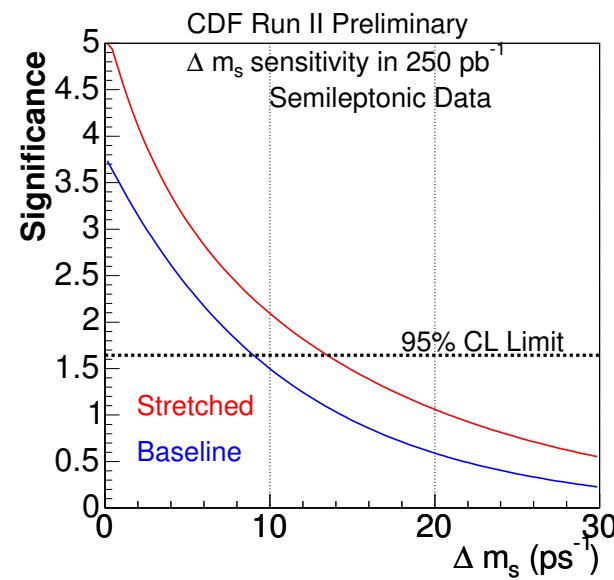
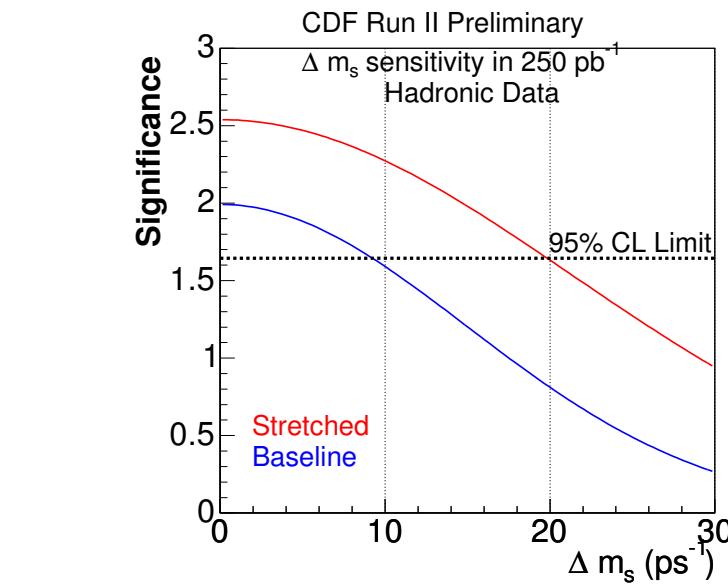
## “Baseline” Scenario

- $\sigma_{ct} = 67 \text{ fs}$   
(w/o event vertex + L00)
- $\epsilon D^2 = 1.6\%$  (w/o SST)  
everything already available

## “Stretched” Scenario

- $\sigma_{ct} = 47 \text{ fs}$   
(with event vertex + L00)
- $\epsilon D^2 = 2.6\%$  (with SST)  
modest improvements

# $B_s$ Mixing Projections (II)

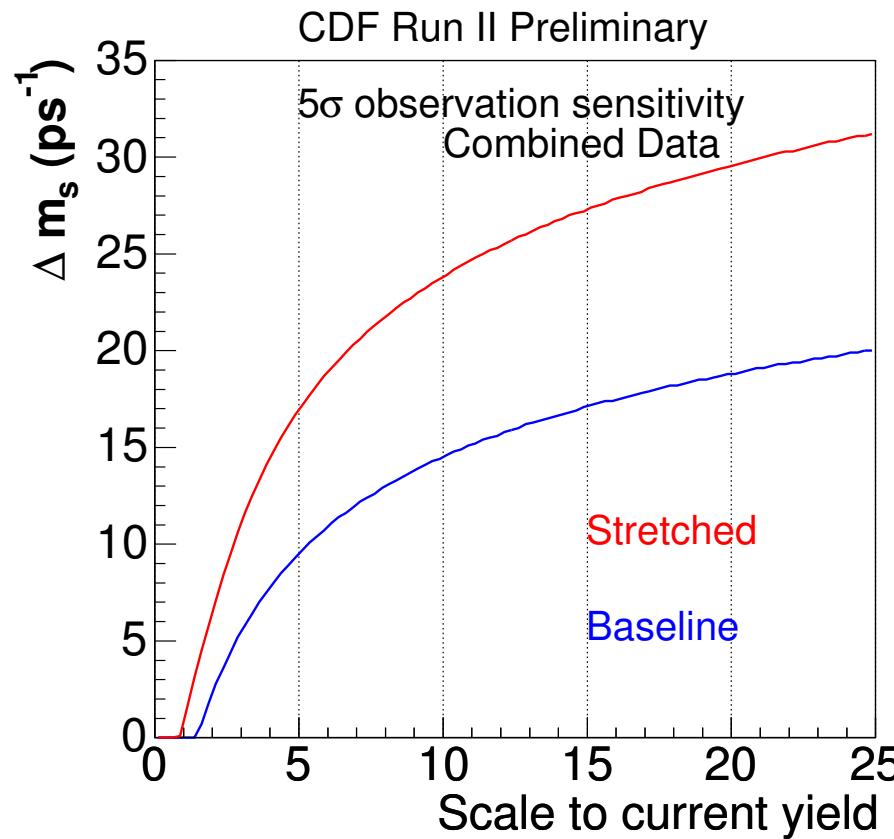


With sample of  $250 \text{ pb}^{-1}$  we are able to set a 95% limit on  $\Delta m_s$ :

	hadronic	semileptonic	combined
baseline	$9 \text{ ps}^{-1}$	$9 \text{ ps}^{-1}$	$14 \text{ ps}^{-1}$
stretched	$20 \text{ ps}^{-1}$	$14 \text{ ps}^{-1}$	$23 \text{ ps}^{-1}$

Our present sample is  $360 \text{ pb}^{-1}$

A little bit further away ...



\* Due to coming dynamic prescaling, projections in terms of luminosity are not available

- Ingredients for  $\Delta m_s$  measurement (limit) are in place
  - Hadronic and semileptonic  $B_s$  modes are reconstructed
  - Opposite side muon, electron and jet-charge tagger in place
  - Setup has been successfully tested for  $\Delta m_d$
- A couple of things need still to be refined
  - Implementation of SVT bias
  - Unbinned likelihood fit
- Projections for  $250 \text{ pb}^{-1}$  data:  $14\text{-}23 \text{ ps}^{-1}$  for setting 95% CL
- $5\sigma$  observation:  $16$  ( $24$ )  $\text{ps}^{-1}$  need five (ten) times more data
- further improvements expected from Same Side Tagger, particle ID, Layer 00 and event vertex